

Precursor of Sunspot Penumbra Formation discovered with Hinode SOT Observations

Toshifumi Shimizu¹, Kiyoshi Ichimoto², and Yoshinori Suematsu³

Received _____; accepted _____

To be submitted to the Astrophysical Journal Letters.

¹Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan. Email: shimizu.toshifumi@isas.jaxa.jp

²Kwasan and Hida Observatories, Kyoto University, Kamitakara-cho, Takayama, Gifu 506-1314, Japan.

³National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan.

ABSTRACT

We present observations of a precursory signature that would be helpful for understanding the formation process of sunspot penumbrae. The *Hinode* Solar Optical Telescope successfully captured the entire evolution of a sunspot from the pore to a large well-developed sunspot with penumbra in an emerging flux region appeared in NOAA Active Region 11039. We found an annular zone (width 3''-5'') surrounding the umbra (pore) in Ca II H images before the penumbra is formed around the umbra. The penumbra was developed as if to fill the annular zone. The annular zone shows weak magnetogram signals, meaning less magnetic flux or highly inclined fields there. Pre-existing ambient magnetic field islands were moved to be distributed at the outer edge of the annular zone and did not come into the zone. There is no strong systematic flow patterns in the zone, but we occasionally observed small magnetic flux patches streaming out. The observations indicate that the annular zone is different from sunspot moat flow region and that it represents the structure in the chromosphere. We conclude that the annular zone reflects the formation of a magnetic canopy overlying the region surrounding the umbra at the chromospheric level, much before the formation of the penumbra at the photospheric level. The magnetic field structure in the chromosphere needs to be considered in the formation process of the penumbrae.

Subject headings: Sun: photosphere — Sun: magnetic topology — Sun: chromosphere — sunspots

1. Introduction

Sunspots are dark patches on the solar surface and the most readily visible manifestations of magnetic flux concentrations (Solanki 2003; Thomas & Weiss 2008). A well-developed sunspot typically consists of a dark central region called the umbra which is surrounded by a less dark, annular region called the penumbra. Sunspots appear with successive series of magnetic flux emergence, in which magnetic flux rises through the convection zone to the solar surface and penetrates into the upper atmosphere. Pores, which are essentially small sunspots without penumbra or naked umbra, are first formed at the both edges of emerging flux regions. Pores are developed to large sunspot with penumbra through the coalescence of pores and smaller magnetic flux tubes into a single, growing pore. When the pore has grown to sufficient total magnetic flux ($1 - 1.5 \times 10^{20}$ Mx), it forms a penumbra in sectors (Leka & Skumanich 1998). The formation of a penumbra is a sudden event, generally within 20-30 minutes, and the Evershed flows are observed without delay after the penumbral formation (Leka & Skumanich 1998; Yang et al. 2003). Recently Schlichenmaier et al. (2010a) showed that the size of the umbral area is unchanged during the growth of the penumbra in about 4 hrs, and concluded that the umbra has reached an upper size limit (about 4Mm in diameter) and that any newly emerging magnetic flux that joins the spot is linked to the process of penumbral formation.

However, the formation process of sunspot penumbra is difficult to catch observationally, especially with high spatial resolution. Because of this, we poorly understand the formation process and have not yet answered fundamental questions, such as why do sunspots have penumbrae? and what causes their rapid formation? Here we present an unique data set from high-cadence filtergraph observations of the *Hinode* Solar Optical Telescope (SOT), which successfully captured the entire evolution of a leading sunspot from the pore to a well-developed sunspot with penumbra (section 2). We discover **an annular**

zone surrounding the umbra in Ca II H before the penumbra is formed around the umbra (section 3), and discuss what is the **annular** structure in section 4.

2. Observations and data analysis

The observations were carried out by SOT (Tsuneta et al. 2008; Suematsu et al. 2008; Shimizu et al. 2008; Ichimoto et al. 2008) onboard *Hinode* (Kosugi et al. 2007). The SOT continuously monitored NOAA Active Region 11039 from December 29, 2009 to January 2, 2010 with some short interruptions for XRT (X-Ray Telescope) synoptic observations. In the SOT field of view, a large emerging flux region appeared from December 30 to 31 and we completely captured the overall evolution from the birth of pore to the development of the large sunspot at the leading area. The region was located at S28 W07 on December 30 and at S27 W22 on December 31. Broadband Filter Imager took Ca II H (3968\AA , band width: 3\AA) images every 3 minutes and G-band (4305\AA , band width: 8\AA) images every 2 hours with 2×2 pixel summation ($0.10896''$). Narrowband Filter Imager acquired longitudinal magnetograms ($0.160''/\text{pixel}$) in Na I D (5896\AA) every 3 minutes. The spectral bandwidth of the Lyot filter is $90\text{m}\text{\AA}$. The magnetograms were derived with the observable named MG4 V/I (Obs ID 85), in which **a pair of I+V and I-V was measured at $+140\text{m}\text{\AA}$ off position four times and V/I was calculated on board after accumulating the 4 pairs for better S/N.** No spectro-polarimeter (SP) data was available in the period before the penumbral formation.

The time series of SOT images were aligned in respect to the solar rotation, which was followed by the spacecraft attitude pointing with a tracking curve (rotation rate is 0.00014805 deg/s) (Shimizu et al. 2007). A cross correlation method was applied with a large field-of-view (FOV) to obtain the series of aligned images. In addition, G-band images acquired by XRT (Golub et al. 2007; Kano et al. 2008) were used to remove small gradual

FOV drifts in the time series due to proper motion of the solar features and intensity gradient in the field of view (Shimizu et al. 2008). The magnetogram conversion to the flux density (gauss or Mx cm^{-2}) is determined by comparing the magnetogram to the magnetic flux density map derived from **SP data** taken at 13:44-14:05 UT on December 31 for the region outside the sunspot.

3. Results

Figure 1 is the temporal evolution of the sunspot seen in G-band and Ca II H every about 2 hrs. Frequent appearance of emerging magnetic patches was observed at the east side of the spot. The penumbra formed in sectors; the penumbra was developed at the north side, and then it formed at the west and south. Note that remarkable chromospheric dynamics associated with the elongated structure formed in the umbra, is out of scope in this paper and will be discussed in a separate paper. Figure 2 is the time-slice of Ca II H images for the slit located across the sunspot. The slit center is shown on Ca II H images in Figure 1 and the average intensity in the width of ± 7 pixels from the slit center is given in the time-slice. The umbra is drifted toward the west with a speed of 0.22 km s^{-1} . On the slit, the development of the penumbra was observed from 6UT to 8 UT on December 31. We can easily notice **a zone between the umbra and ambient bright features** before the penumbral formation. This zone appeared soon after the pore formation and was seen for about 10 hrs until the penumbral formation. The zone is annular with the width of $3''$ - $5''$ in Ca II H images. **In the Ca II H image at the left of Figure 1, the zone exists at the outer side of the umbral edge (indicated by the dotted contour) on almost all the locations excepting the east side of the spot. Its brightness is almost similar to that inside the network cells far from the sunspot. The penumbra was developed as if to fill the annular zone. The zone became very dark after the**

penumbral formation and its brightness is 58 – 73% of the brightness in the quiet-Sun network cells.

The corresponding time-slice of Na I D magnetograms is shown in Figure 3. The annular zone shows weak signals; the magnetic flux there is less line-of-sight component or highly inclined. A remarkable behavior is the existence of positive-polarity (the same polarity with the sunspot) magnetic flux concentrated at the outer edge of the zone. This flux is pre-existing flux patches and may be observed as bright features in Ca II H (Figure 2). The sunspot was developed in the region where the dominant magnetic flux polarity is same as that of the sunspot. The pre-existing flux patches that come to the outer edge of the zone moved to west in response to the motion of the sunspot, and they did not come into inside the zone. The total ambient flux located at the west side of the sunspot is almost constant (2.5×10^{20} Mx) within ± 15 % in between before and after the penumbral formation. **Note that we measured the total flux of ambient magnetic patches existing in the zone within ± 13.6 arcsec from the position of the slit center outside the annular zone or penumbra.** The total magnetic flux of the sunspot monotonically increased with time and it was 5×10^{20} Mx at 3 UT and 7×10^{20} Mx at 6 UT on December 31.

Gas flow patterns inside the zone before the penumbral formation were examined with 3-minutes cadence time series of Na I D magnetograms (Figure 4 and a supplemental movie). We observed some flux patches that flow out from the edge of the spot and move outward. **Cellular** patterns, in which most of flux is distributed at **cellular** edge, were formed in between the spot and the ambient field (arrows in Figure 4). The **cellular** patterns were gradually evolved to an annular structure. There were no strong systematic flow patterns in the annular zone, which is quite different from the moat region, but a **limited number of** outward moving patches were observed, as shown in Figure 4 (a) and

(b). The speed of these moving patches is $1 - 2 \text{ km s}^{-1}$. In the zone, no magnetic patches were observed to show inward motion to the umbra. **It is noted that the flux patches moving toward the umbra were frequently observed on the east side of the spot where flux emergence took place actively**(Schlichenmaier et al. 2010b). After the penumbral formation, we observed that small magnetic patches frequently flow out from around the penumbral edge.

4. Discussion and conclusions

Ca II H images newly revealed that **an** annular zone exists surrounding the pore before the formation of penumbra. Here we discuss the physical nature of the annular zone.

First, the annular zone is the structure different from sunspot moat region. The moat region is an annular region outside the penumbra with a persistent large-scale radial outflow (moat flows) and **frequent appearance of** moving magnetic features (Sheeley 1969; Harvey & Harvey 1973). Since the penumbra is developed as if to fill the pre-existing annular zone **and a systematic moat-flow-like outflow is not observed in the annular zone**, we can conclude that the annular zone represents the structure different from the moat. Second, the annular zone has its origin in higher atmosphere, i.e., chromosphere. This is because the zone can be found in chromospheric Ca II H images but the corresponding signature cannot be seen in photospheric G-band images.

A possible interpretation is that the annular zone may reflect the formation of a magnetic canopy at the chromospheric level overlying the region surrounding the umbra, much before the formation of the penumbra at the photospheric level (Figure 5). Hurlburt & Rucklidge (2000) conducted numerical simulations on axisymmetric flux tubes in a compressible convecting atmosphere and shows how the magnetic field configuration

changes as a function of magnetic flux, i.e., from a small pore to a well-developed sunspot. The potential magnetic field is used in the atmosphere above the photospheric layer. Because of the pressure balance with surrounding gas that has a decreasing pressure at higher atmosphere, the flux tube forms a canopy configuration in the layer above the photosphere. They showed that the size of the canopy structure is almost independent of the total flux content of the flux tube, which is in good agreement with the almost constant width of the annular zone (3-5") in the entire period from the pore formation to the penumbral formation. Because of magnetic pressure of the canopy fields, ambient pre-existing magnetic flux elements cannot move into inside the annular zone.

In the penumbrae, the average inclination of the magnetic field increases from approximately 40 deg at the umbra-penumbra boundary to about 70 deg at the outer edge of penumbra (**Bellot Rubio et al. 2003**). There is no obvious gradual increase in the field inclination during the formation of penumbrae (Leka & Skumanich 1998). Thus, the appearance of penumbra would be quite sensitive to the field inclination at the edge of the umbra. The magnetic fields at the edge of umbra are extended to the chromosphere and corona. The magnetic field structures created in the chromosphere may give influence to the field inclination at the photosphere. According to recent numerical simulations of sunspot models, the development of penumbra appears to be quite sensitive to the magnetic field structure in the chromosphere. Rempel et al. (2009) provided the first MHD simulations of the entire sunspot structure that resolve sunspot fine structures and their dynamics. The vertical domain size of their simulations is still small and the top boundary condition is located only about 700 km above the quiet-Sun $\tau = 1$ level. With a different boundary condition at the top, the numerical runs result in a different penumbral structure of the simulated sunspot, including no penumbral formation (Rempel 2011b). Rapid penumbral decay is also observed in association with major flares, suggesting that the penumbral structure at the photospheric level can be significantly influenced by magnetic field topology

in the corona (Wang et al. 2004; Deng et al. 2005).

It was observed that **a limited number of** small magnetic flux patches stream out at the photosphere below the chromospheric canopy structure. **The frequency of the outgoing patches tells that the emergence from below the photosphere in the annular zone is not the origin for the appearance of the penumbral magnetic features.** Earlier observations show that motions toward the pore dominate in the 1''-2'' zone around the pore boundary and their average speed is $0.3\text{-}0.5 \text{ km s}^{-1}$, while at larger distances the granules move away from the pore with the speed much slower than 1 km s^{-1} (Keil et al. 1999; Sobotka et al. 1999). Bipolar moving magnetic features were observed to stream out from a pore (Zuccarello et al. 2009). Recently, Rempel (2011a) made the simulation run to explore the subsurface field and flow structure around the spot without penumbra and compared it with the structure in the run with penumbra. Even in absence of a penumbra, the simulation shows a large-scale radial outflow surrounding the sunspots everywhere in the photosphere, in addition of a converging flow in the proximity of sunspots.

Our observations suggest that the canopy structure is formed in the upper atmosphere, i.e., chromosphere. When unknown conditions are settled in, the chromospheric canopy fields may be evolved to the highly inclined penumbral fields at the photospheric level. **Rezaei et al. (2012) found that, at the early stage of the penumbral formation, the magnetic area of the umbra extends over the visible limits of the penumbra at the photospheric level. There the field strength is fairly high and the field has large inclinations. This is consistent with a forming canopy.** Thus, the observed annular zone structure can be interpreted as the precursor of the penumbral formation. The chromospheric structure surrounding the umbra can depend on the spatial distribution of pre-existing magnetic flux elements surrounding the umbra and their magnetic polarity. In the case presented in this paper, the pre-existing flux is same as the umbra's, and therefore

an annular canopy structure is formed in the area between the flux-concentrated umbra and ambient flux patches, as illustrated in Figure 5. The existence of ambient flux patches may keep the canopy fields from going down to the photospheric level. If the ambient field has opposite sign, an annular canopy structure may not be well developed around the umbra, because magnetic reconnection can easily take place in between the umbral field and ambient field. Thus, we point out the possibility that different development of chromospheric structures around the umbrae may lead to different development of penumbrae, which should be studied observationally with more examples in the future.

We conclude that the annular feature in Ca II H reflects the formation of a magnetic canopy overlying the region surrounding the umbra at the chromosphere and that the canopy structure may play an important role in the formation of penumbrae. Further investigations in the magnetic structures at both the chromosphere and the photosphere are urgently needed in coming years.

The authors would like to express their thanks to Dr. Y. Katsukawa for data analysis and Drs. M. Rempel and B. Lites for fruitful comments. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). This work was partially supported by KAKENHI 23540278.

REFERENCES

- Bellot Rubio, L.R. et al. 2003, A&A, 403, L47
- Deng, N. et al. 2005, ApJ, 623, 1195
- Golub, L. et al., 2007, Solar Physics, 243, 63
- Harvey, K. & Harvey, J. 1973, Solar Physics, 28, 61
- Hurlburt, N.E. & Rucklidge, A.M. 2000, MNRAS, 314, 793
- Ichimoto, K. et al. 2008, Solar Physics, 249, 233
- Kano, R. et al. 2008, Solar Physics, 249, 263
- Keil, S.L., Balasubramaniam, K.S., Smaldone, L.A. & Reger, B. 1999, ApJ, 510, 422
- Kosugi, T. et al. 2007, Sol. Phys., 243, 3
- Leka, K.D. & Skumanich, A. 1998, ApJ, 507, 454
- Rempel, M. et al. 2009, Science, 325, 171
- Rempel, M. 2011a, ApJ, 740, 15
- Rempel, M. 2011b, private communication
- Rezaei, R., Bello González, N. & Schlichenmaier, R. 2012, A&A, 537, A19
- Schlichenmaier R., Rezaei, R., Bello González, N., & Waldmann, T.A. 2010, A&A, 512, L1
- Schlichenmaier R., Bello González, N., Rezaei, R., & Waldmann, T.A. 2010, Astron. Nachr., 331, 563
- Sheeley, , N.R.Jr. 1969, Solar Physics, 9, 347

Shimizu, T. et al. 2007, PASJ, 59, S845

Shimizu, T. et al. 2008, Solar Physics, 249, 221

Sobotka, M. et al. 1999, ApJ, 511, 436

Solanki, S.K. 2003, A&A Rev., 11, 153

Suematsu, Y. et al. 2008, Solar Physics, 249, 197

Tsuneta, S. et al. 2008, Solar Physics, 249, 167

Thomas, J.H. & Weiss, N.O. 2008, Sunspots and Starspots, Cambridge University Press:
Cambridge

Wang, H. et al. 2004, ApJ, 601, L195

Yang, G., Xu, Y., Wang, H., & Denker, C. 2003, ApJ, 597, 1190

Zuccarello, F. et al. 2009, A&A, 500, L5

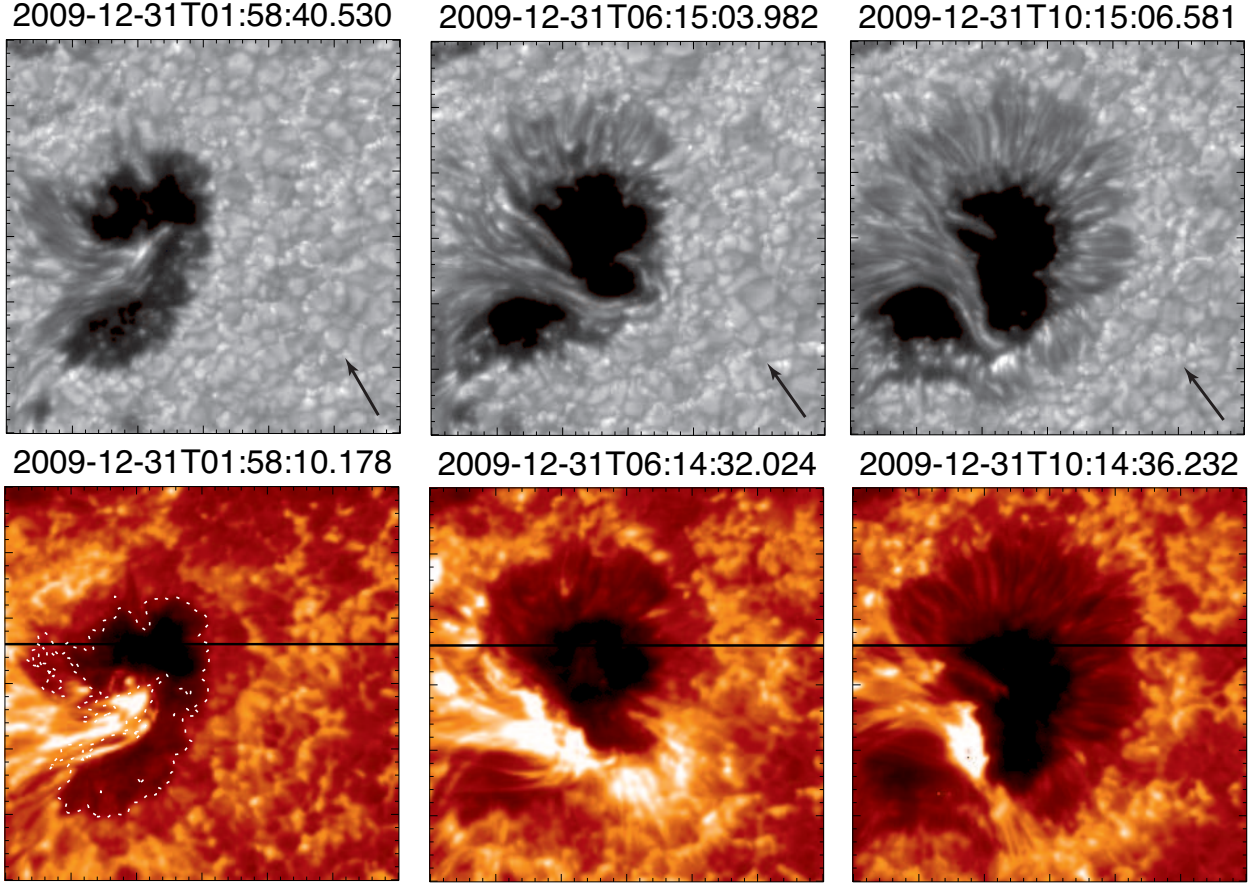


Fig. 1.— Evolution of the sunspot seen in G-band and Ca II H every about 4 hrs. North is up and east is left. The field of view is $32.7'' \times 32.7''$ (300×300 pixels). The horizontal line in Ca II H images indicates the position of the slit center for generating the time-slice maps in Figure 2 and Figure 3. **The arrows are pointing to disk center and the dotted line is the umbral edge.**

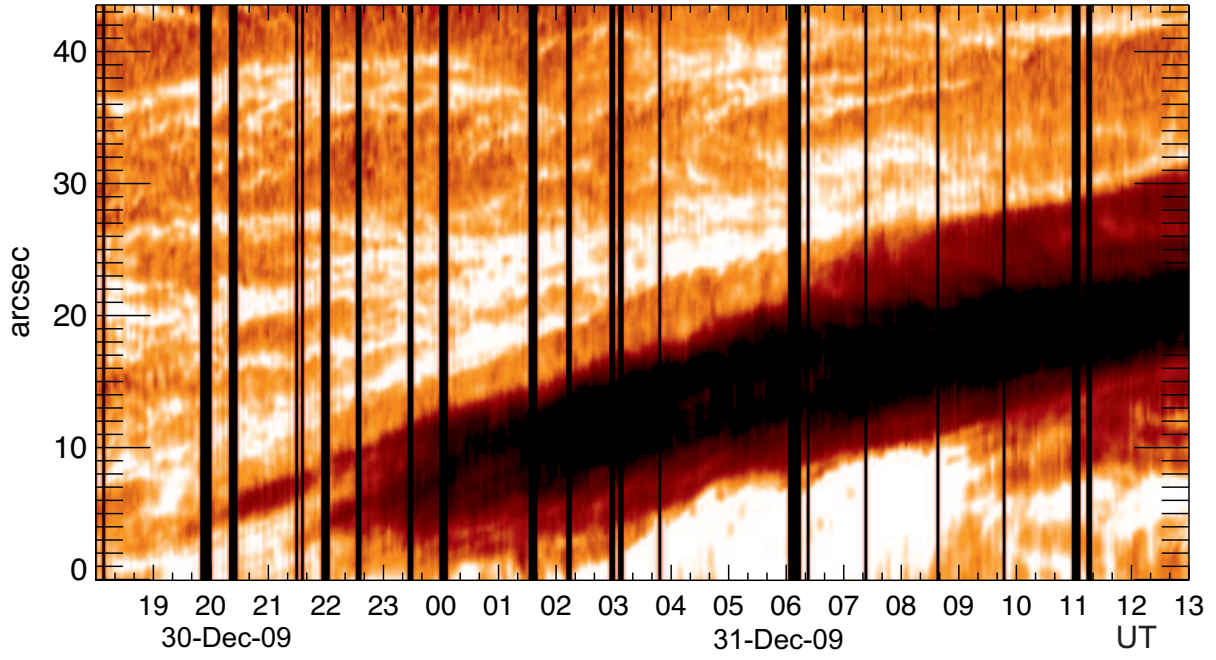


Fig. 2.— Time-slice of Ca II H images for the slit located across the sunspot. The slit center is shown on Ca II H images in Figure 1. The larger values in the slit position mean toward the west. The black stripes are data gaps.

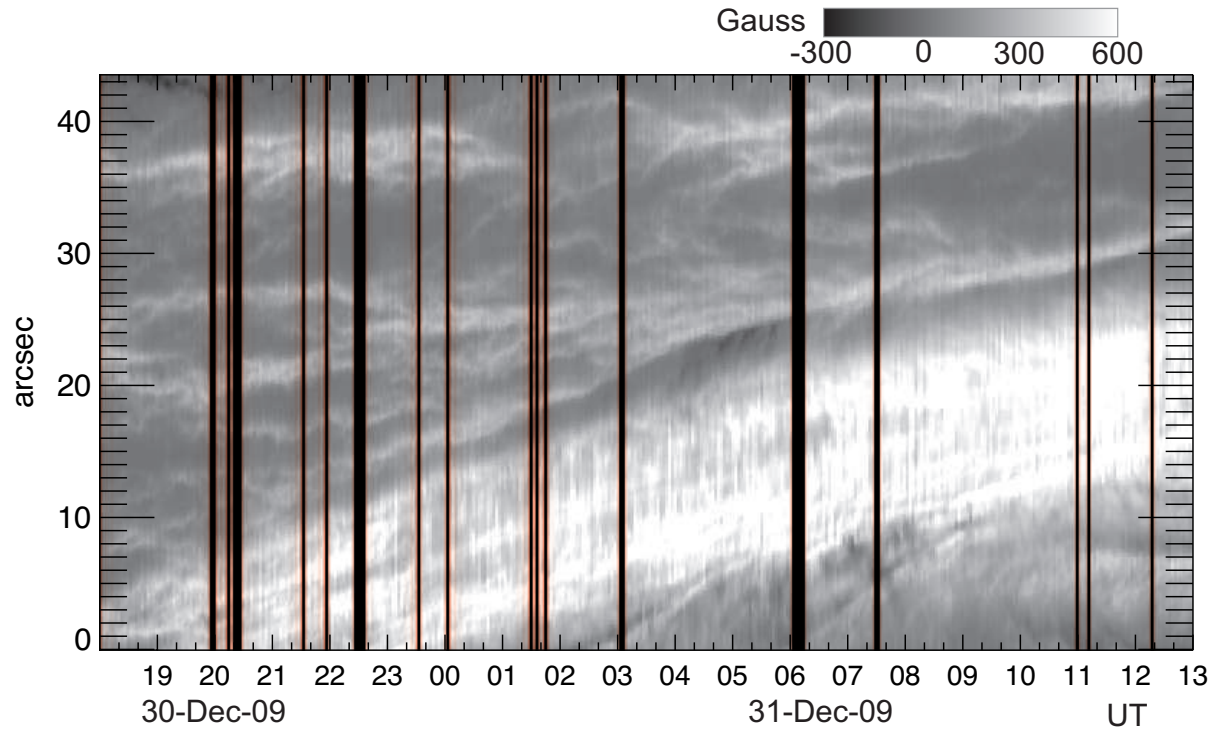


Fig. 3.— Time-slice of Na I D magnetograms. See Figure 2 for details. **Note that the data is clipped as given in the scale bar.**

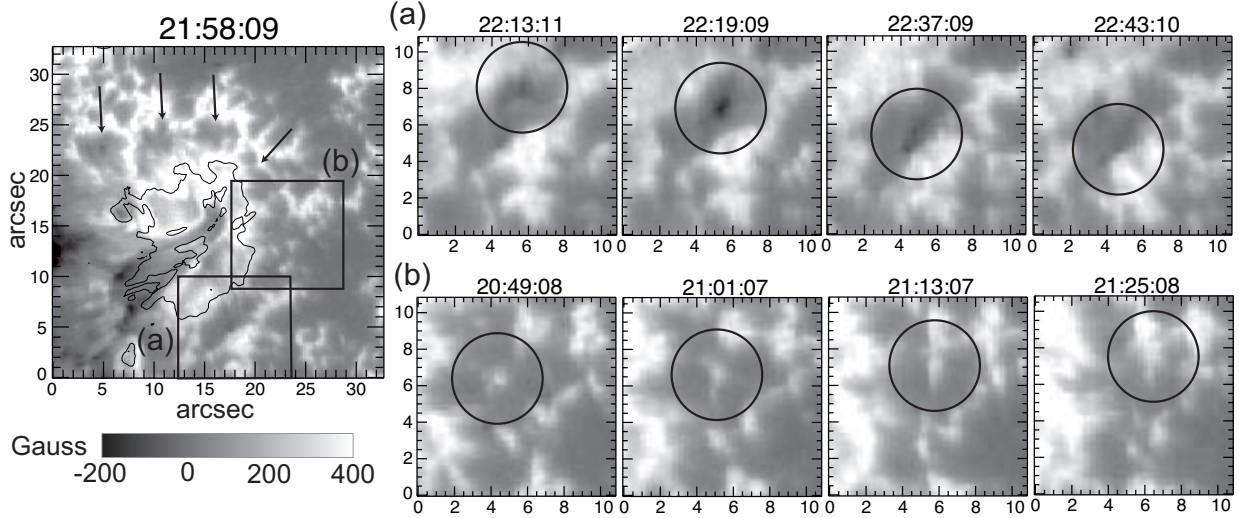


Fig. 4.— Temporal evolution of Na I D magnetograms in two regions located in the annular zone, labeled as a and b. Circles (5 arcsec in diameter) indicate the position of an outward moving patch. The field of view is $10.9'' \times 10.9''$. North is up and east is left. The solid contour in the large field-of-view image gives the outer boundary of the pore determined with a G-band image.

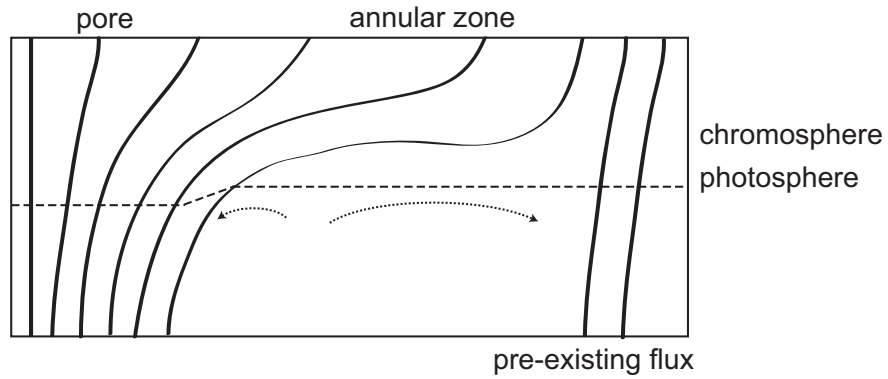


Fig. 5.— Magnetic field structure before the penumbral formation. The nearly horizontal dash line indicates the photospheric ($\tau = 1$) level. The dotted lines with the arrow head are large-scale gas flows in the subsurface layer.